# CHAPTER 4

## Ship Operations

4-1. Introduction. Deep-draft navigation projects are built or improved to enhance the safety, efficiency, and productivity of waterborne commerce in U.S. ports and harbors. To properly assess navigation traffic in the waterway channels, the planner and designer must understand ship behavior in ports and harbors and the main operational factors having an impact on navigation. This chapter presents the necessary ship operation information required by the analyst and highlights important impacts on channel design.

4-2. Navigation System. The proper design of navigation channels requires an understanding of port and harbor operations viewed as a system. Generally, at least three components or viewpoints are relevant as listed below with a brief outline of each:

*a.* *Waterway engineering subsystem*.

(1) Navigation channels design and maintenance.

(2) Environmental factors wind, waves, tides, and currents.

(3) Dredging and mapping services.

(4) Shore docking facilities.

*b.* *Marine traffic subsystem*.

(1) Operational rules and regulations.

(2) Aids to navigation.

(3) Pilot and tug service.

(4) Information and data sources.

(5) Communications and vessel traffic services (VTS).

*c.* *Vessel hydrodynamic subsystem.*

(1) Ship design.

(2) Maneuverability and controllability.

(3) Human factors.

(4) Navigation equipment.

The important point is that each of the three subsystems cannot be considered without information from the other two subsystems. Therefore, the channel designer is required to analyze the total system in an integrated fashion, taking into account the ship factors and the traffic factors to produce an adequate design. It should also be clear that tradeoffs between investments for the three subsystems are not only possible but are normal procedure. Thus, the channel dimensions often dictate ship design and placement of aids to navigation; the converse of this is also true, i.e., that the channel design is heavily influenced by the ship sizes and the available accuracy of aids to navigation.

4-3. Typical Operations.

*a.* The methods used during typical ship transits into and out of ports are of major concern to the navigation designer since they guide the design process. Ships at sea will give notice to the local port authority and pilot group several days out upon approaching the port entrance. A local shipping agent or firm is usually also involved as the commercial chartering entity acting in the business transaction between the cargo shipping entity, the ship owners offering transportation services, and the destination company ordering or requesting the commodity. Upon arrival at the entrance, the ship will be met while underway or at anchor by one or more locally licensed pilots who provide the navigation service guiding the ship safely to the proper berth or terminal. The boat meeting and pilot transfer to the ship take place at a designated anchorage area located near the ocean end of the entrance channel marked by a sea buoy. Local tug services are also usually contacted and plans finalized for the ship transit. Many tug companies also provide a tug pilot who will also board the ship to help guide the ship during the final phase of the transit and the actual docking and mooring at the ship berth. At some ports, the local pilot also acts as the tug docking pilot.

*b.* Upon reaching the ship bridge, the pilot confers with the ship master or watch officer on the ship particulars: namely, engine power, rudder, navigation equipment, and loading condition (draft and trim). Legally, the pilot is only an advisor, so that the ship captain still has responsibility for the ship. In practice, the pilot takes control of the ship, issuing rudder and engine commands as well as course orders.

*c.* The process of steering and controlling the ship in a channel is typical of a feedback control system as depicted in Figure 4-1. The transit into a port follows a series of straight segments of the navigation channel centerline by a process of course keeping where the pilot gives course settings, and the steersman monitors and changes the rudder setting to maintain the ship heading. If currents or wind effects are important, the pilot will carefully keep an eye on the course, changing the heading to correct for any set by those forces. The engine rpm may be constant or may be changed during the straight legs but often is reduced to “slow” or “dead slow” for speed reduction. Ships are usually maintained at high maneuvering speeds, if possible, which are less than sea speeds. For most ships, transit speeds in the straight channel segments may be up to 12 knots (6.1 m/sec (20.2 ft /sec)) if traffic is light and without any particular hazards.

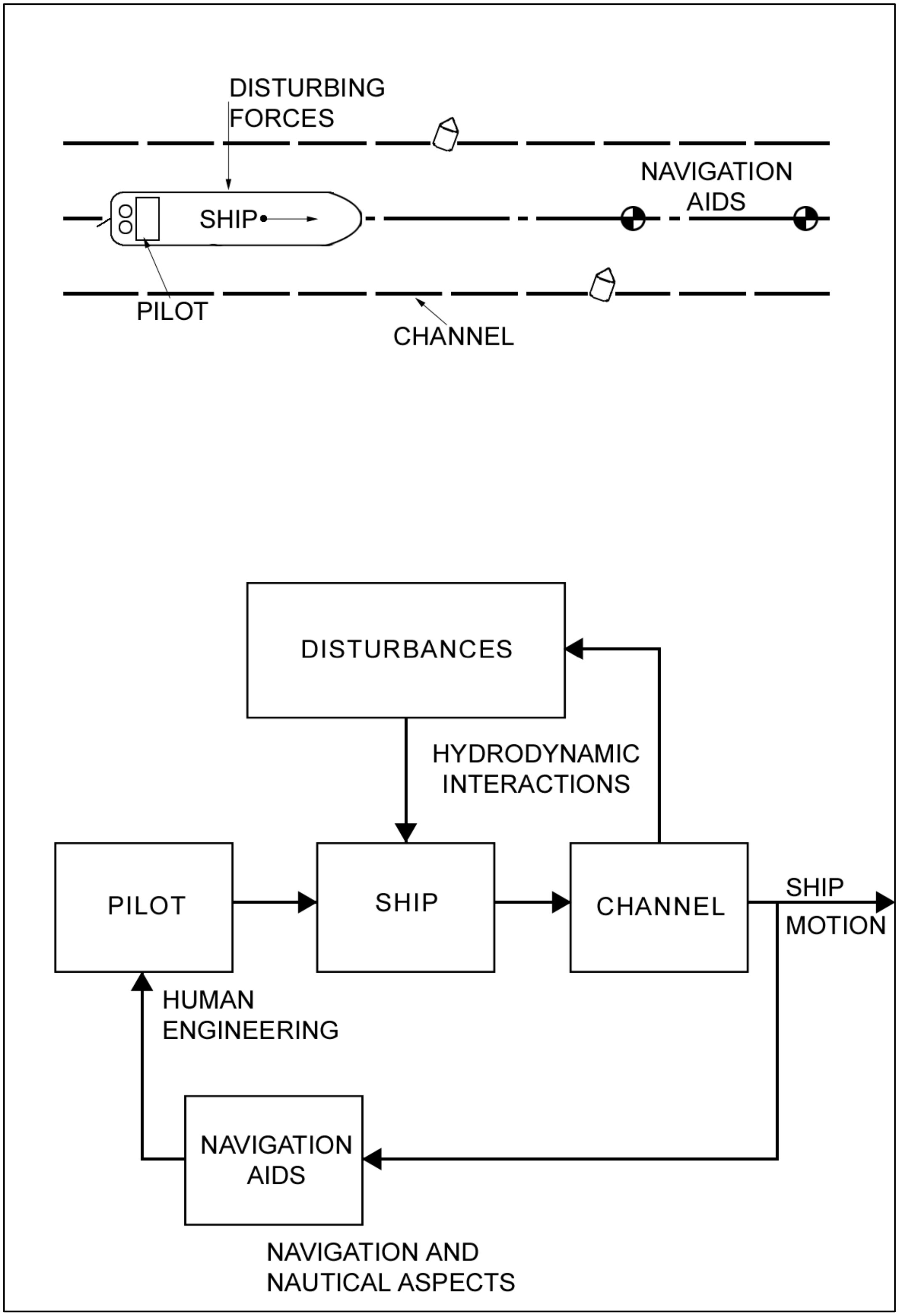


Figure 4-1. Ship control system

*d.* Specific rudder commands are issued to the steersman upon approaching a channel turn, such as “right--20 degrees,” etc. The engine rpm setting is often briefly changed to “full ahead” to provide the kick to start the ship turning. The channel turns or way points are locations where special caution is required as a result of rapid changes in ship position with respect to channel banks and current effects. A small-turn angle is usually easy; the larger angular turns (say 30 or more degrees) are often much more difficult. Pilots familiar with the channels know when to issue the proper commands and how to monitor the ship response and will not hesitate to give "full right rudder" if it seems necessary. In some ports, specially difficult circumstances along the transit may occur, such as at very narrow overhead bridges or meeting or overtaking situations. The port entrance channel is often particularly troublesome because of complex crosscurrents, waves, frequent shoaling problems, and wind effects. Difficult control situations will demand special diligence and specific rudder and engine commands by the pilot.

*e.* The ship is slowed down well before approaching the berth or terminal, usually with the assistance of tugs when ship control is lost at speeds below 3 to 4 knots (1.5 to 2.0 m/sec (5.0 to 6.7 ft/sec)). The upper end of most port channel systems usually includes many docks, terminals, small craft harbors, and other forms of congestion, which call for very slow speeds to prevent waves and moored ship hawser breakage. The final phase of the ship transit is with the tugs pushing the ship to the dock face and mooring lines made fast to the ship and the dock.

*f.* The outbound ship transit from the berth back to the open sea where control is transferred from the local pilot to the master is much the same as the inbound transit, except in reverse sequence.

*g.* The normal ship transit sequence of events outlined above should not obscure the fact that ships can always be brought into a port by operational modifications, provided the channel depth and width are adequate. If need be, the timing of the transit can be changed to avoid wind, currents, or other difficult environmental factors. Alternatively, use of adequate tugs to handle the ship as a tow is possible. Such operations, however, would not usually provide an economically viable solution. Navigation channels are thus designed to allow normal ship handling under ship self-powered operation at sufficient speeds over a wide operational window to provide an adequate port throughput for economic viability.

## 4-4. <u>Ship Resistance.</u>

*a.* Overall ship resistance is an important parameter that has been thoroughly studied by naval architects since this determines the power required to propel a ship. A ship-like body moving through a fluid is a fundamental concept in understanding resistance. An example of such a moving body submerged in deep water is depicted in Figure 4-2. Ideal potential flow fluid theory shows that positive pressure is produced on each end of the body with negative pressures along the ship middle body. Because of viscous effects from real fluids on the body surface, a boundary layer is generated along the body causing body frictional resistance. Flow separation will occur at the ship stern, causing increased resistance from eddy drag. The sum total viscous and eddy resistance of the ship is called the wetted surface drag and can be readily calculated or obtained from tabulated towing tank data.

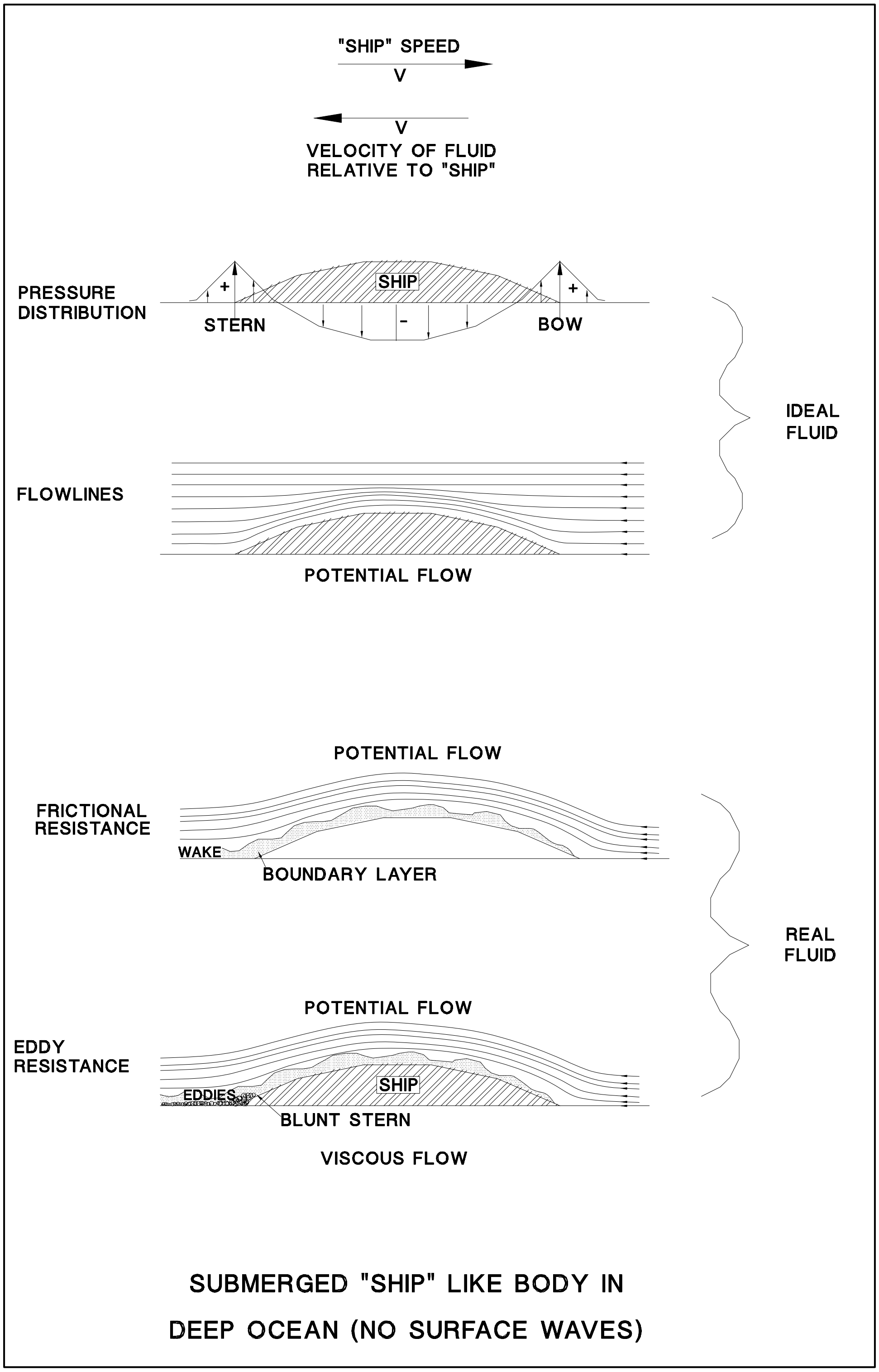


Figure 4-2. Submerged shiplike body

*b.* The ideal pressure distribution on the moving ship in deep water causes a system of waves on the free surface moving with the ship. The fact that a ship sailing over the deep ocean at constant speed generates a wave system is well known by any sailor or casual observer. As shown in Figure 4-3, these waves are composed of both divergent and transverse waves and are generated at the bow and the stern of the ship as well as at various positions along the ship length. The waves at the free surface waterline are generated by the pressure distribution around the ship and cause significant resistance to the ship. More important to the navigation planner and designer is that the ship also sinks and trims with respect to the static ship. Thus, the ship will sink in the water and trim because of the wave train caused by the ship. While this occurs in deep water, the waves and ship sinkage become much more prominent in shallow water. The wave making by the ship, therefore, has an important impact on the design of the channel.

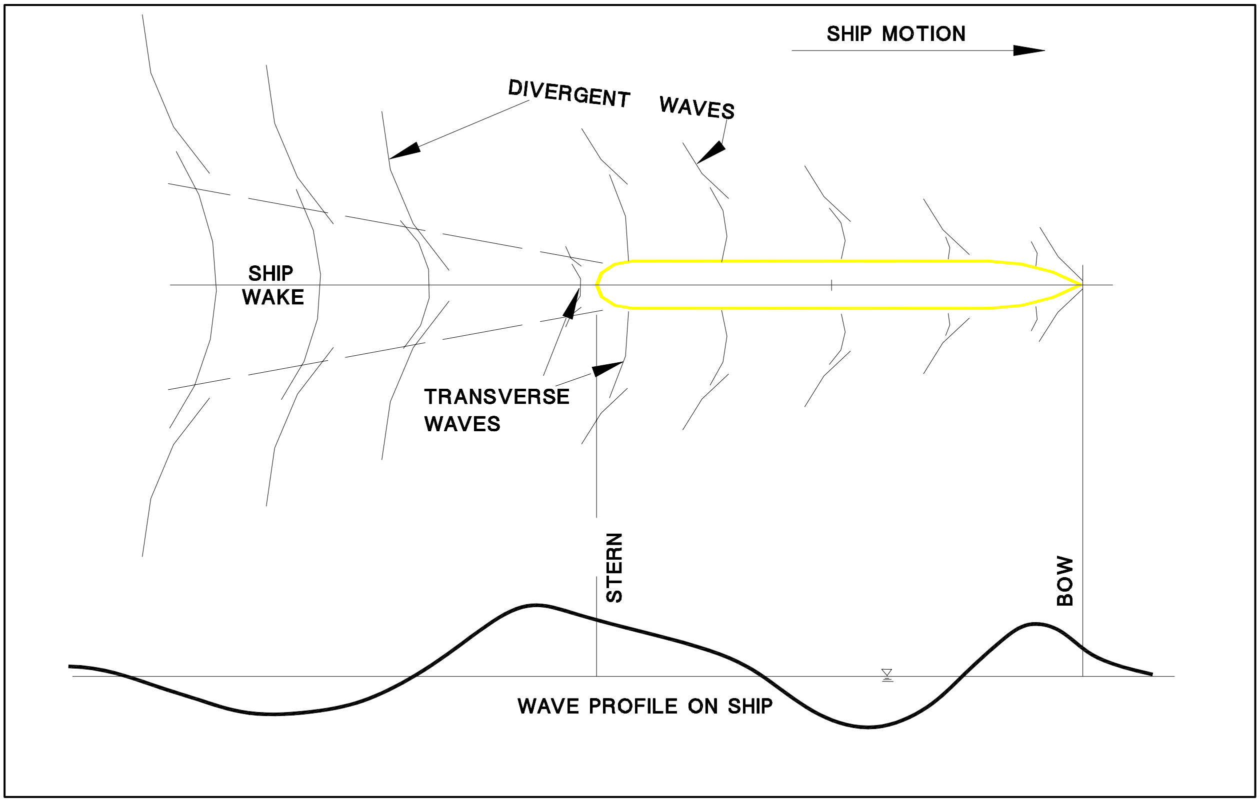


Figure 4-3. Schematic of ship wave system

*c.* At very low speeds, most of the ship's resistance is the result of wetted surface drag; as the speed is increased, wave-making drag grows higher. The ship length Froude number ($F_l$) has been an important parameter in determining wave effects. This may be given as the ratio of ship's speed to the square root of the acceleration because of gravity and the ship's length:

$$F_l = \frac{V}{\sqrt{gL}} \tag{4-1}$$

where

$F_l$ = ship's length Froude number

$V$ = ship's speed in meters (feet) per sec

$g$ = acceleration as a result of gravity in meters (feet) per sec$^2$

$L$ = ship's length in meters (feet)

The normal value of this dimensionless parameter is usually very small for commercial ships — perhaps varying from near 0.04 for tankers at slow ship speeds near 5 knots (2.6 m/sec (8.4 ft/sec)) to near 0.40 for fine-line containerships at 25 knots (12.8 m/sec (42.0 ft/sec)). Navy warships, which may operate at much higher speeds, of course, would sail at higher design Froude numbers. Wave drag becomes increasingly important at Froude numbers of about 0.2 or higher and can become two or three times the ship's surface resistance at Froude numbers of 0.4.

*d.* The total drag on a ship determines the selection of the ship thrust and power required to sail the ship at the design speed. The engine power is crucially important in the maneuverability of the ship, especially at the typical moderate harbor speeds, when engine acceleration effects are used to provide kick turns. The ratio of installed engine shaft horsepower to the ship deadweight tonnage may be called specific power and used to relate the relative ship powered maneuverability. Values of the ship specific power vary from about 0.05 to 50 for displacement ships of various types, both naval warships and maritime commerce. The values for warships are listed in Table 4-1.

Table 4-1
Ship Specific Power

| Ship | Specific Power | Maximum Speed, knots |
|---|---|---|
| Battleship | 3.7 | 35 |
| Cruiser | 6.5 | 35 |
| Destroyer | 19.0 | 35 |

The evolution of tankers from the small 13,000-dwt size with typical specific power ratio of about 0.5 has grown progressively smaller to under 0.1 at the highest 500,000-dwt size. While these power levels are adequate to move the ships at the design speed, their ability to accelerate and decelerate is significantly impaired.

4-5. <u>Shallow Water.</u> The resistance of a ship increases appreciably in shallow water because of speed increases around the ship's hull and changes of the wave pattern. The effects of shallow water can be characterized by the simple ratio of water depth ($h$) to ship draft, ($T$). The increased frictional resistance and wave patterns in shallow water both modify the sinkage and running trim and the squat of a ship and required underkeel clearance. For most merchant ships, which travel at 25 knots (12.8 m/sec (42.0 ft/sec)) or less, this effect becomes important when water depth-to-ship draft ratios ($h/T$) are less than 4.0. Since most ship navigation channels operate at very small depth to draft ratios (typically $h/T$ less than 1.5), shallow-water effects have major impacts on ship navigation. The important parameter that governs ship waves in shallow water is the depth Froude number:

$$F_h = \frac{V}{\sqrt{gh}} \tag{4-2}$$

where

$F_h$ = depth Froude number

$V$ = ship speed in meters/sec (feet/sec)

$h$ = water depth in meters (feet)

As the ship speed increases, the shallow-water effects will increase up to the value of depth Froude number equal to unity, where critical open channel flow would occur. In practice, wave effects, squat and running trim, and ship resistance become very high at $F_h$ values well below $F_h = 1.0$, so that normally a self-propelled merchant ship would not exceed $F_h$ of about 0.6.

4-6. Restricted Channels.

*a.* A further increase of wave effects, squat, and ship resistance occurs when ships sail in navigation channels. The ratio of midship cross-sectional area (normally, $A_s$ is ship beam times draft or $B$ T), and the channel cross section ($A_c$) is used to characterize the relative channel restriction (see Figure 4-4 for a definition sketch). The inverse of the above value of ship area ($A_s$) to channel area ($A_c$) is often described as the channel blockage ratio ($B_R$). Typical channel blockage ratios may vary from 2 to 3 for very restricted narrow canals and channels up to situations with open channels at ratios of 20 or more. The critical depth Froude number will change accordingly from $F_h = 0.2$ at $B_R = 2$ to $F_h = 0.7$ at $B_R = 20$ as shown in Figure 4-4. The Schijf limiting velocity, to be further discussed in Chapter 6, imposes an upper limit on the ship speed for self-propelled ships sailing in restricted channels, especially canals. For the normal channel blockage ratio from about 3 to 10, this can be an important limitation. For example, at $B_R = 3$ in 12.2-m (40-ft) water depth, the maximum ship speed is about 6.4 knots (3.3 m/sec (10.8 ft/sec)). Even at a $B_R = 10$ in 15.2 m (50 ft) of water, the maximum ship speed is 14.3 knots (7.3 m/sec (24.0 ft/sec)).

*b.* These considerations assume the ship engine has the power and thrust to overcome the ship resistance. The restricted channel, the increased return currents, and wave effects cause a substantial ship resistance above deep-water, oceangoing conditions. Figure 4-5 presents the flow pattern and drawdown accompanying a ship sailing in a canal. Extensive towing tank testing in Sweden (Norrbin 1986) has resulted in the development of relationships that describe the ship power and speed loss as a function of depth of water and channel blockage. This diagram is presented in Figure 4-6. Ship propeller rpm and delivered power to drive the ship are reduced in shallow water and canal blockage. The diagram shows that for a ship in shallow water typical of many channels at depth-to-ship draft ratio of about 1.1, only 70 percent of the ship design sea speed could be sustained. A typical tanker designed to achieve 15 to 16 knots (7.7 to 8.2 m/sec (25.2 to 26.9 ft/sec)) in the open ocean would thus sail at about 11 knots (5.6 m/sec (18.5 ft/sec)) in shallow water.

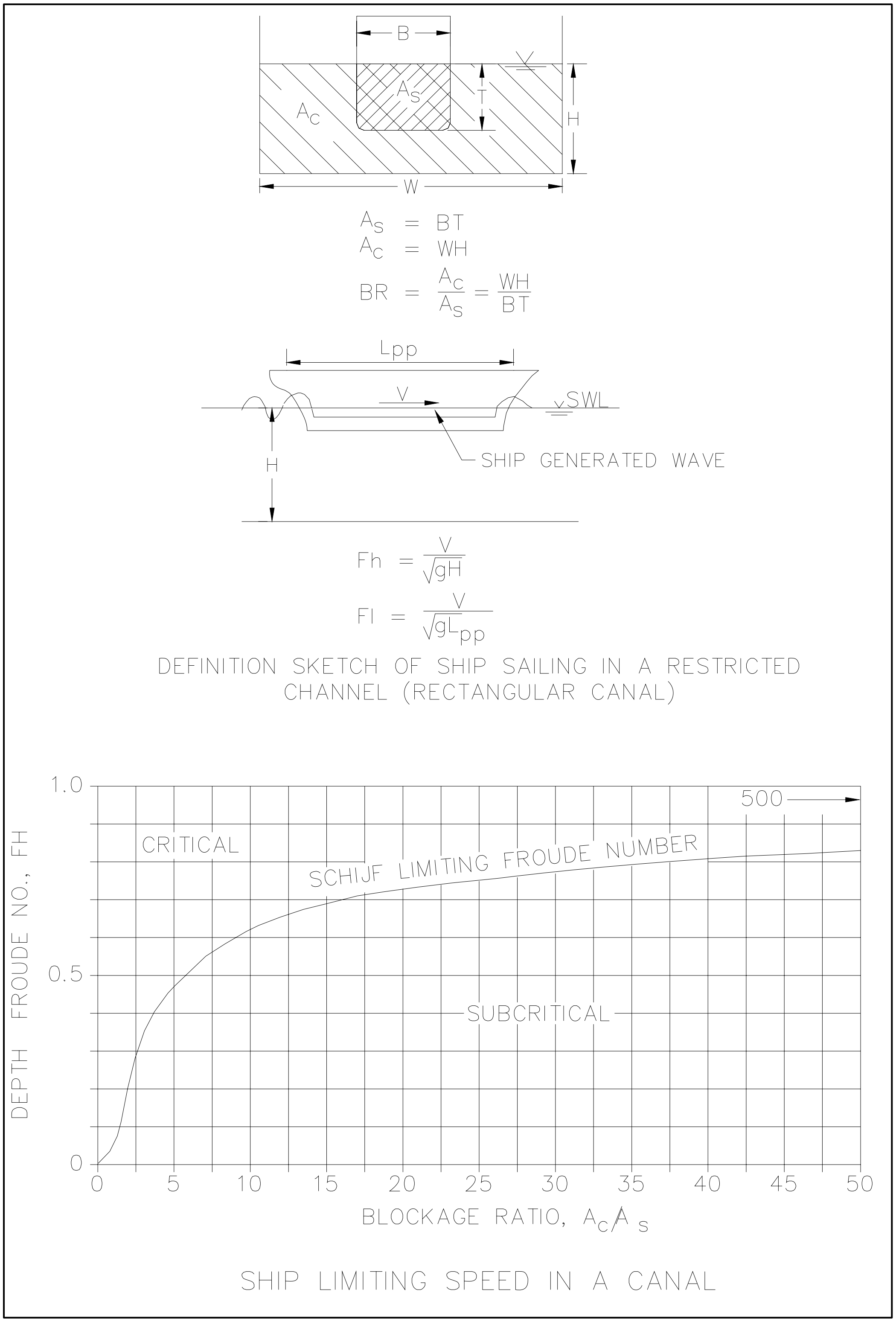


Figure 4-4. Ship limiting speed in a canal

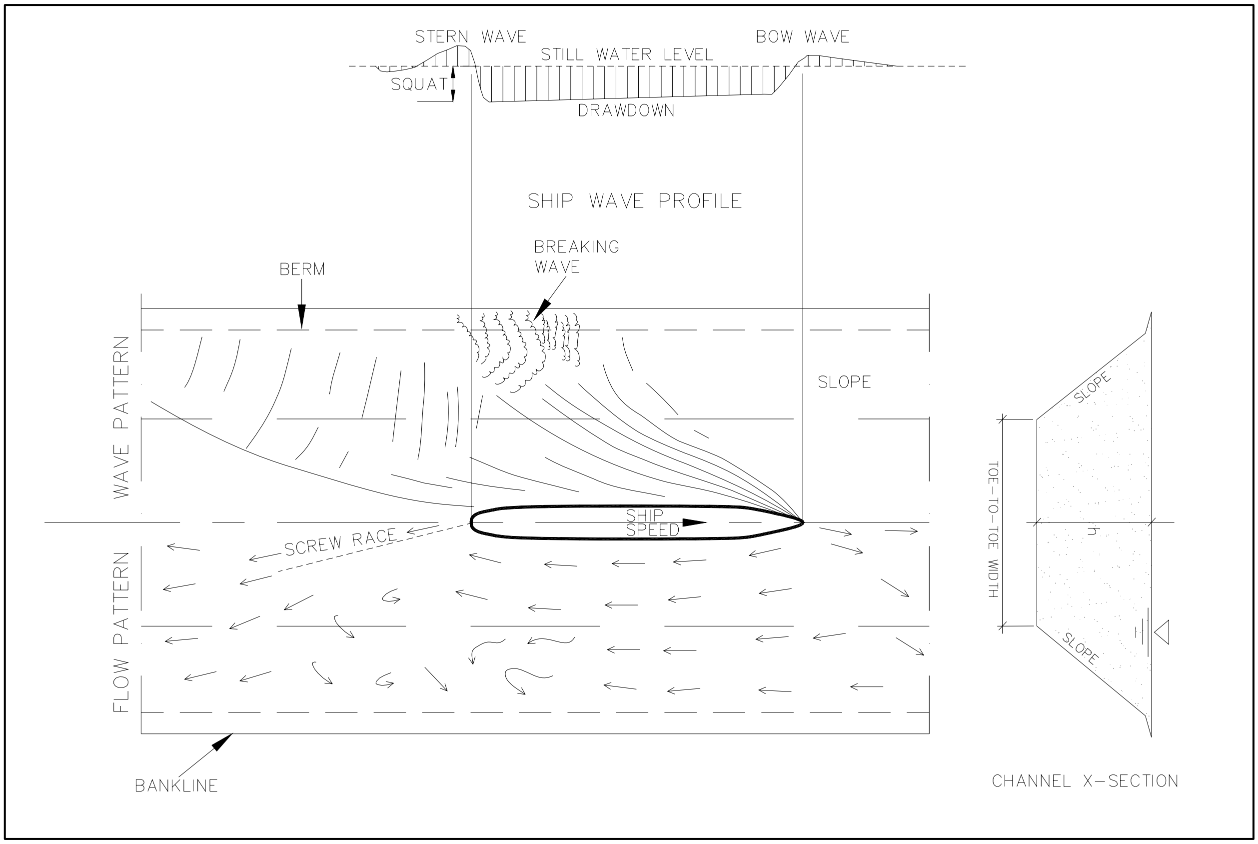


Figure 4-5. Ship wave and flow pattern in a canal

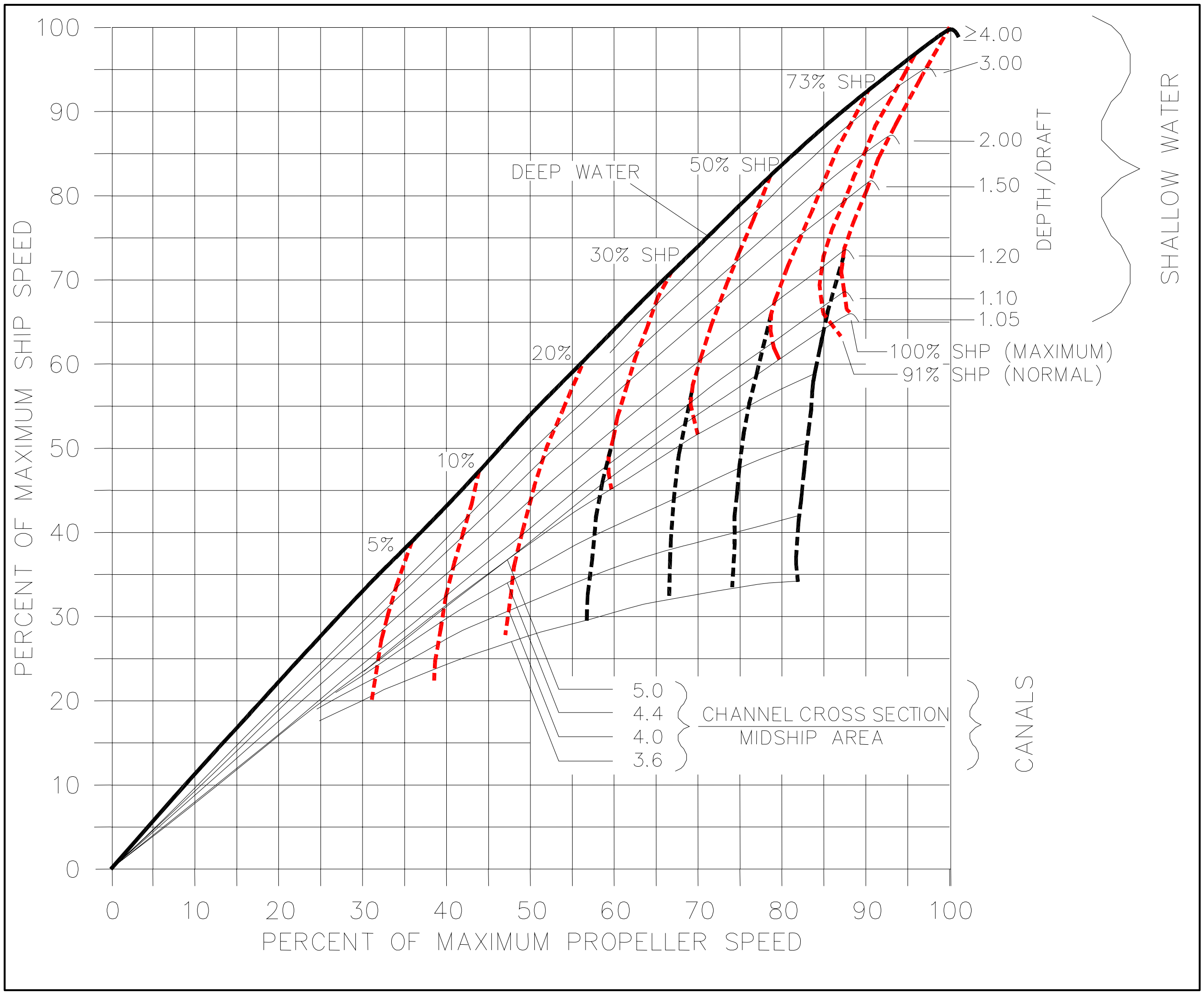


Figure 4-6. Ship speed relation in restricted waters for typical tankers